13:52:53 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 03/31/92

Active

Project #: E-25-M64 Cost share #: Rev #: 3
Center # : 10/24-6-R7257-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: N00014-91-J-1972 Mod #: P00001 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: 12.AAA
Main project #: PE #:

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
BAIR S S III MECH ENGR (404)894-3273

Sponsor/division names: NAVY / OFC OF NAVAL RESEARCH
Sponsor/division codes: 103 / 025

Award period: 910701 to 921230 (performance) 921230 (reports)

Sponsor amount	New this change	Total to date
Contract value	75,000.00	106,659.00
Funded	75,000.00	106,659.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: DEFORMATION BEHAVIOR OF THIN LUBRICANT FILMS AT ELEVATED PRESSURE

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U
Defense priority rating : N/A
Equipment title vests with: Sponsor

ONR resident rep. is ACO (Y/N): Y
ONR supplemental sheet
GIT X

Administrative comments -
MOD #P00001 FUNDS DR. BAIR'S 8/12/91 PROPOSAL, ADDS $75,000 THROUGH 12/30/92.

SR154
2-
2-

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 06/23/93

Project No. E-25-M64 | Center No. 10/24-6-R7257-0A0

Project Director BAIR S S III | School/Lab MECH ENGR

Sponsor NAVY/OFC OF NAVAL RESEARCH

Contract/Grant No. N00014-91-J-1972 | Contract Entity GTRC

Prime Contract No. ____

Title DEFORMATION BEHAVIOR OF THIN LUBRICANT FILMS AT ELEVATED PRESSURE

Effective Completion Date 921230 (Performance) 921230 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsEFFECTIVE DATE 7-1-91. CONTRACT VALUE $106,659.

Subproject Under Main Project No. ____

Continues Project No. ____

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other CARL BAXTER-FMD	Y
FRED CAIN-OOD	Y

NOTE: Final Patent Questionnaire sent to PDPI.

E25-M64

DEFORMATION BEHAVIOR OF THIN LUBRICANT FILMS AT ELEVATED PRESSURE

June, 1993

A Report to the

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800 North Quincy Street
Arlington, VA 22017-5000

by

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INTRODUCTION

Elastohydrodynamic (EHD) lubricated contacts occur in most machine components that are used to transmit force or motion. In EHD contacts the surfaces under high pressure (up to 4 GPa) are separated by thin but continuous liquid films that are sheared at high rates (up to 10^8 s^{-1}). The rheological deformation behavior of liquid lubricants governs the film formation and the average shear stress (or traction) that can be transmitted across an elastohydrodynamic (EHD) lubricated contact. Although the linear Newtonian model is successful in determining the film thickness of an EHD contact, it fails to realistically predict the traction behavior of such a contact. It had long been observed that the maximum traction of an EHD contact is always limited to a certain fraction of the pressure at the contact. This observation led Smith (1959) to propose a model on the basis of such a limiting maximum value of shear stress of a lubricant. The maximum attainable shear stress in a lubricant has been termed limiting shear stress. The limiting shear stress of lubricants was not measured until 1979 (Bair and Winer (1979)). Their results were later supported by additional primary high-pressure results (Bair and Winer (1990), Ramesh and Clifton (1987)).

The phenomenon of limiting shear stress is illustrated in Figure 1. that shows the flow curve of two different lubricants under steady shear. The experimental conditions were such that the local temperature rise did not affect the rheological properties of the liquids. Logarithm of shear stress (τ) is plotted against logarithm of shear strain rate ($\dot{\gamma}$) for a polyphenyl ether (5P4E) and a mineral oil (N1). A linear proportional (Newtonian) relationship exists at low shear rates. The Newtonian region is then followed by a non-proportional transition regime that leads to rate independent plastic shearing of the lubricant at a constant limiting shear stress (τ_L). Based on their primary data Bair and Winer (1979) proposed a model which has the following functional form:

$$\dot{\gamma} = \tau_L/\mu \ln(1-\tau/\tau_L) \qquad (1)$$

Since the glass transition temperature increases with pressure, one would expect that at typical EHD pressures, many lubricants will be in a glassy state. This was confirmed by experimental observations of AlSaad et.al. (1978). An evidence of glass transition would indicate that there may be an analogy in the deformation behavior of liquid lubricants under pressure and solid amorphous polymers. In Fig. 1. the ratio of pressure to glass transition pressure is indicated by P^*.

Although, the phenomenon of limiting shear stress has been well established, and is accepted by most researchers in the area of tribology and lubricant rheology, a firm theoretical understanding of the physics of such a behavior had been missing. Previously, the transition from Newtonian to rate independent behavior has been attributed to a process based on Eyring's theory (Johnson et.al. (1977)). It has also been postulated that the slip may occur at the boundaries (Johnson et.al. (1988)) or there may be a gross slip in the bulk of the material (AlSaad et al (1978)). A single experimental study by Kaneta et.al. (1990) has been performed that inconclusively supports an argument that wall slip may occur in an EHD contact.

Since lubricants are in general poor thermal conductors, for a continuously shearing lubricant minimal heat conduction away from the shear region and into the boundaries occurs. This leads to a local temperature rise resulting in the alteration of the properties of the lubricant and increase local shear rates for a stress controlled experiment resulting in a thermal runaway.

The objective of this paper is to present a fundamental experimental investigation into shear deformation behavior of liquid lubricants under varied conditions of pressure, temperature and shear rate. The experiments have been designed so that the experimental liquids are sheared in a steady simple shear mode by imparting linear uni-directional motion to a shear boundary by application of a constant force to the shear boundary. A flow visualization technique has been used and the experimental conditions are varied so that the extreme regimes of isothermal and adiabatic idealization are approached.

EXPERIMENTAL

An experiment was designed for evaluation of the mechanisms of shear rheological deformation of liquid lubricants under pressure. The shear geometry is shown in Fig. 2. The lubricant under study is sheared in simple, steady mode between two parallel surfaces.

The end of a stationary pin and a ground flat on a shaft that traverses in a longitudinal direction constitute the parallel plate geometry. Essential features of a high pressure flow visualization cell that incorporates this geometry are shown in Fig. 3. The cell can be pressurized to 0.3 GPa and the material under shear can be observed through sapphire window in the top of the cell. The details of the construction and operation are listed elsewhere (Bair et.al. (1992a)). A flow visualization technique that incorporates micro glass spheres (of 2 μm diameter) as tracer particles has been used to determine if the velocity profiles are continuous across the gap. Each experimental sequence constitutes a uni-directional movement of the shaft. A velocity discontinuity in the gap will indicate the existence of a shear localization in the direction of shear at the location of such a discontinuity. The details of the optics used in the study are also outlined previously (Bair et.al. (1992a)). Experimental liquids that range from mineral oil, synthetic hydrocarbons, and medium and high molecular weight polybutenes have been used in the study. The liquids have been selected on the basis of their characterization for their rheological properties and lubrication performance (Johnson (1986), Bair and Winer (1992)). The influence of tracer particles on the lubricant viscosity was studied. Based on high-pressure viscosity measurements it was concluded that the viscosity of the lubricants was not altered due to tracer particles. The time averaged velocity profiles across the gap were traced by following the displacement of particles as a function of time. The total force acting on the stationary pin due to material shear in the gap and the material flowing around the pin was measured by the pin deflection.

RESULTS AND DISCUSSION

Velocity Profiling

It was observed that the time averaged velocity profiles remain linear and continuous across the gap even if the shear stress-strain rate relationship indicates a transition to non-linear behavior. Measured velocity profiles in relation to rheological deformation behavior of the liquid are shown in Fig. 4. Although it is difficult to isolate the actual shear stress acting in the gap, the transition from linear to non-proportional increase in shear force with the shear rate is in effect a transition from Newtonian to limiting stress behavior. A s evident from the continuous and linear time averaged velocity profiles, the previously postulated existence of continuous shear localization in the direction of shear can be refuted.

Observation of Shear Bands

Crack-like visual features in the form of bands inclined to the direction of shear were observed during the experiments. These fine crack like features (or bands) were inclined to the shear boundaries and they first appeared in the entrance region of the shear gap, possibly due to stress concentration. The inception of bands was observed to occur as the force strain rate relationship deviated from proportionality. Further increase in strain rate led to profileration of bands. A representation of the appearance of shear bands is shown in Fig. 5. It should be realized that about 10 microns of the gap thickness is obscured due to optical effects near the boundaries. The features of shear bands were different from the birefringence as shown in Fig. 6. that was observed by using crossed polarizers. However, the bands almost always initiated at the point of highest stress in the gap as indicated by the birefringence observations.

The slip of the material accommodated by a shear band can be measured by monitoring the motion of tracer particles across the shear band. This was accomplished by selecting two tracer particles equidistant from the boundaries and then tracing the displacement of the particles as a band appears between them. The particles were observed to exhibit finite relative movement. The angle of inclination of the band was also calculated from the measured slip of particles in the direction of shear and across.

Shear Band Inclination

The shear bands have been observed in four different lubricants over a range of temperature and pressure conditions. The materials with higher limiting shear stress values resulted in higher band inclination angles. The dependence of angle of inclination on the shear gap size, and imposed pressure was also investigated. The pressure and temperature dependance of the experimental fluid regarding its liquid/glass transition properties had already been carried out by AlSaad et.al. (1978). Although it is realized that the glass transition is a fuzzy concept and it is not a well defined point, the flow visualization experiments were carried out at conditions both above and below the glass transition pressure of the experimental fluid as obtained by PVT measurements. The inclination angles of the shear bands remained un-affected during these experiments. The gap size was also varied from 45 μm to about 190 μm and the inclination angles remained un-affected.

Another interesting observation was that, except for the inception of the shear bands in the entrance region, it is hard to predict the location of the shear band appearance. The shear bands have been observed to appear in clusters with unaffected liquid in between. There may be a distribution of critical stress which results in the appearance of shear bands, and the average of this distribution will be the limiting shear stress of the material. The mode of action of a shear band is clearly demonstrated in the sequence in Fig. 7(a)-(d). A foreign liquid particle is visible near the stationary (lower) boundary when there is no shear. As the shearing starts by imparting motion to the upper surface, a shear band develops and progresses towards the lower surface. The shear band cleaves the particles in a half as it progresses towards the stationary boundary. As the shearing stops the particle tends to regain its spherical shape.

The above mentioned experiments were carried out at small gap size and typically low shear rates. However, if the shearing experiments are carried out at higher shear rates with large shear gap size such that the heat generated due to viscous dissipation is not conducted away quickly, another kind of localization may occur. Such a thermal localization is termed "adiabatic shear localization" in the high rate deformation of metals (Bai & Dodd, 1992). It was first recognized by Plint (1967/68) that the viscous heating in an EHD film may result in a thermal localization at the mid plane of the film.

Observation of Thermal Localization

A flow visualization experiment can be designed so that a thermal localization in the field of view can be detected through local changes in temperature. A thermal localization results in local changes in density, and local refractive index. The light being transmitted through the material will therefore react to such local changes in the refractive index. As a result the light rays that encounter a locally hot (lighter) material will be diffracted towards a cooler (denser) material, rendering a visually dark region (hot spot) surrounded by brighter material.

All the experiments described previously were carried out at conditions which do not permit the local temperature to affect the lubricant properties. However, if the conditions are such that the heat generated cannot be effectively conducted away to the boundaries a thermal localization may result. Flow visualization experiments at relatively thick film thickness (150 μm) and high shear rate (on the order of $120 s^{-1}$) were carried out. due to poor thermal conductivity of the lubricants a thermal localization should be expected to occur almost in the mid plane of the film (in the case of a simple shear experiment) as recognized by Plint (1967/68). The parameter which has been used to characterize the thermal behavior of a liquid film in plane Couette shear is the dimensionless Brinkman number

$$Br = \beta \tau^2 h^2 / \mu_o k \qquad (2)$$

Where β is the temperature viscosity coefficient, τ is the shear stress, h is film thickness, μ_o is viscosity at initial temperature, and k is thermal conductivity of the liquid.

In the case of stress controlled experiment, the presence of a thermal localization will lead to very high local shear rates compared to the apparent shear rate. This equivalent to having two cooler and denser layers of liquid sliding against each other with a hotter and lighter material at the interface and will lead to a thermal runaway.

The flow visualization experiments for observation of thermal localization were performed at a sample pressure of 172 MPa at 22°C. An initial velocity of 0.75 mm/s was developed with a shear gap size of 150 μm. The calculated Brinkman number for this flow is 6.75. The central one-third of the length in the shear direction was in the field of view of the camera. The video prints from the recorded video images are shown in Fig. 8. The velocity history is shown in Fig. 9.

It is clearly shown in the sequence in Fig. 8. a dark band appears after 260 ms of the initiation of the experiment. Such a band is absent in the previous video print. The time resolution of the video is limited to 30 ms. The dark band persisted for a few seconds after shearing ceased and then disappeared. The observation of the shear band in almost the midplane is consistent with the fact that the hotter layer of the liquid diffracts the light rays away to the cooler region (near the boundaries). The band is seen to be displaced at one end where cooler liquid is being drawn into the shear region by the moving surface.

CONCLUSIONS

Original experiments were designed and performed for flow visualization of liquids under steady simple shear at high pressure. With plastic shearing of the liquids, continuous slip parallel to the direction of shear as previously postulated has not been observed. Under conditions when the local temperature rise is limited so as not to affect the material properties, the transition from linear Newtonian to non-Newtonian behavior has been observed to be accompanied by the observation of shear bands inclined to the direction of shear. Finite slip along the bands has been measured. The shear bands first appear at the point of maximum stress and progress towards the lower boundary. The existence of intermittent shear bands inclined to the shear boundaries has been presented as a possible mechanism of slip accommodation in liquid lubricants at high shear rates. Although similar kind of bands have previously been reported in the plastic deformation of amorphous polymers (Bowden and Jukes (1972), Bowden and Raha (1970), Haward (1973), Brown Duckett and Ward (1968), and Brown and Ward (1978)), observations in liquids under pressure have first been performed in this work. The inclination angles have been observed to be independent of gap size or pressure, but they were dependant upon the material type.

At bigger gap sizes, and high shear rates when the local temperature rise is substantial so as to decrease the local viscosity, another kind of thermal band parallel to the direction of shear have been observed.

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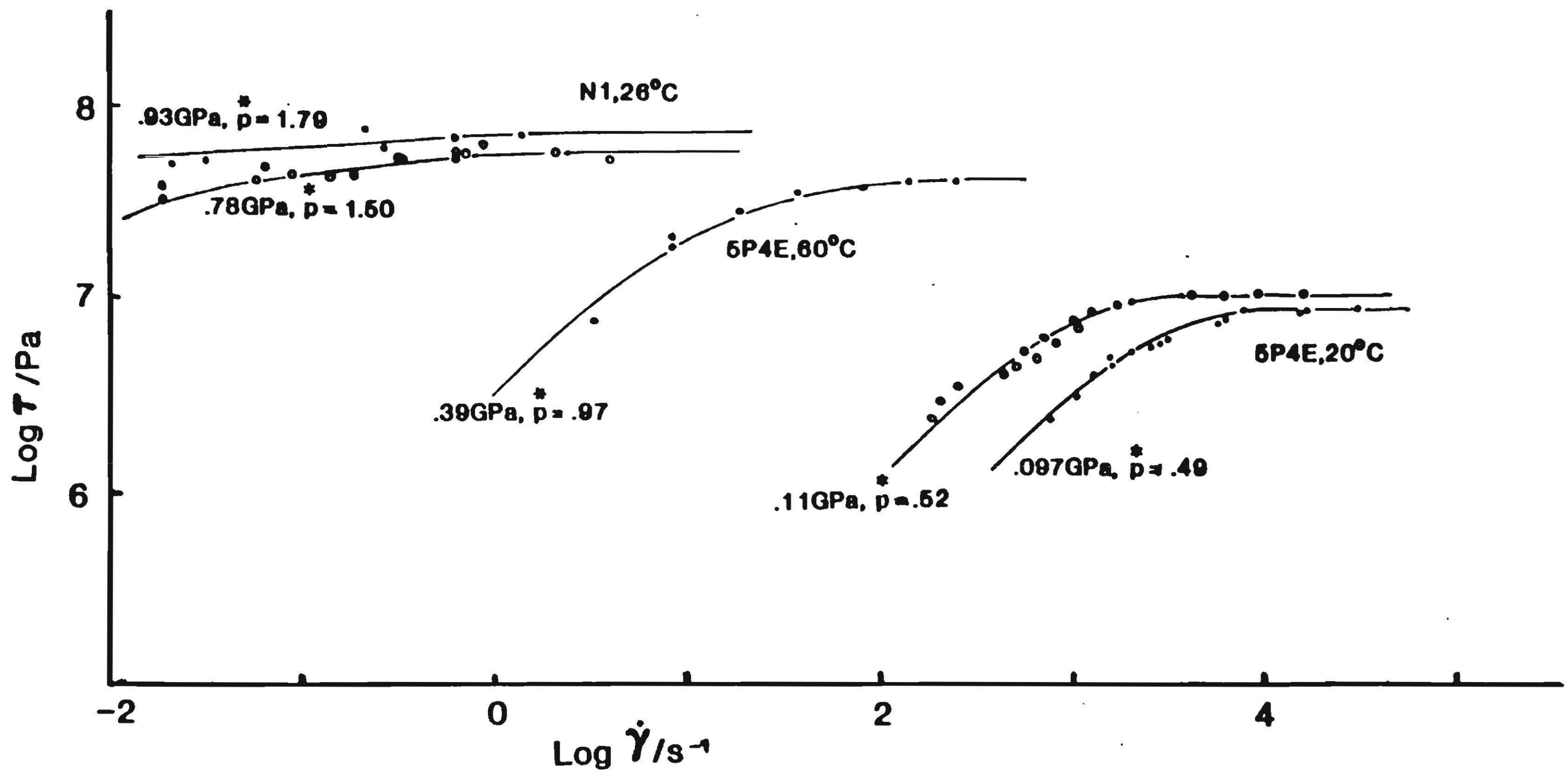


Fig. 1. The Transition from Newtonian to Plastic Flow Under Various Dimensionless Pressures.

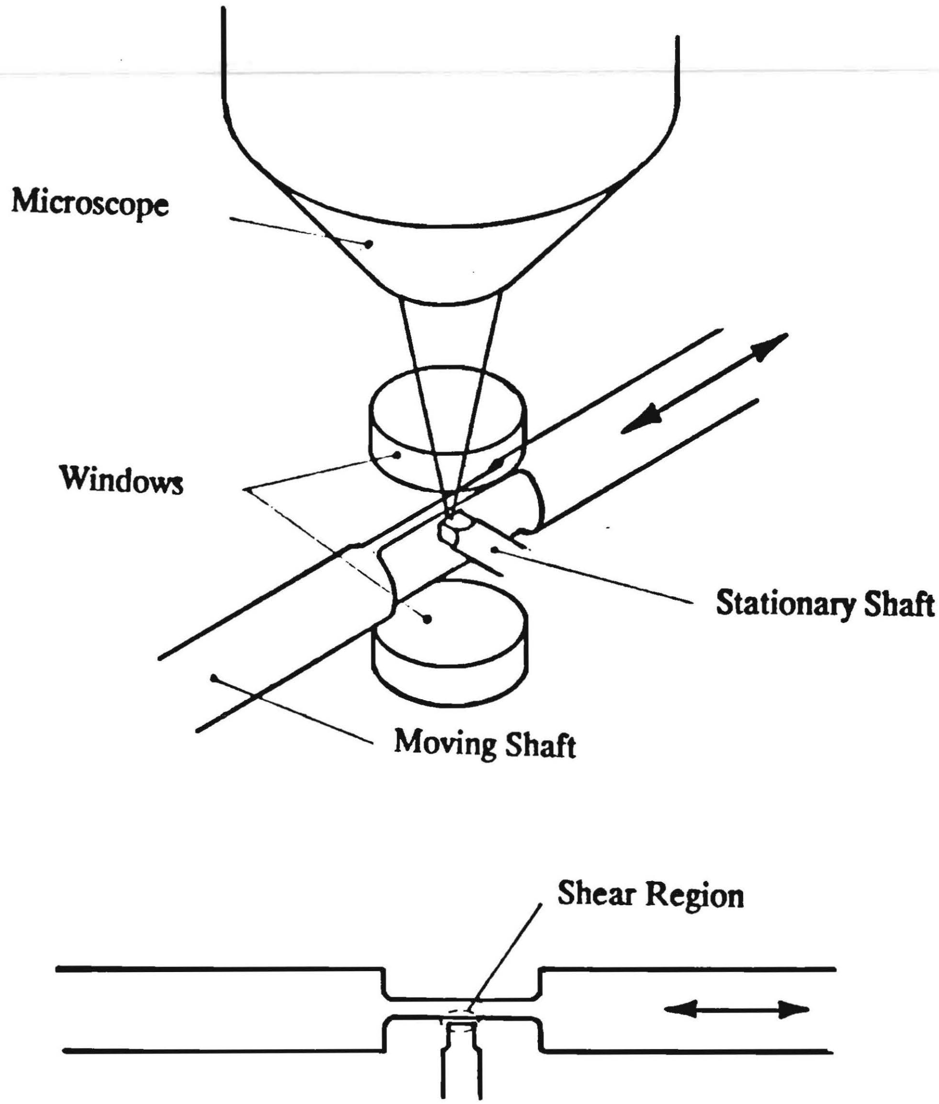


Fig. 2. Simple Shear Geometry used in the Experiments.

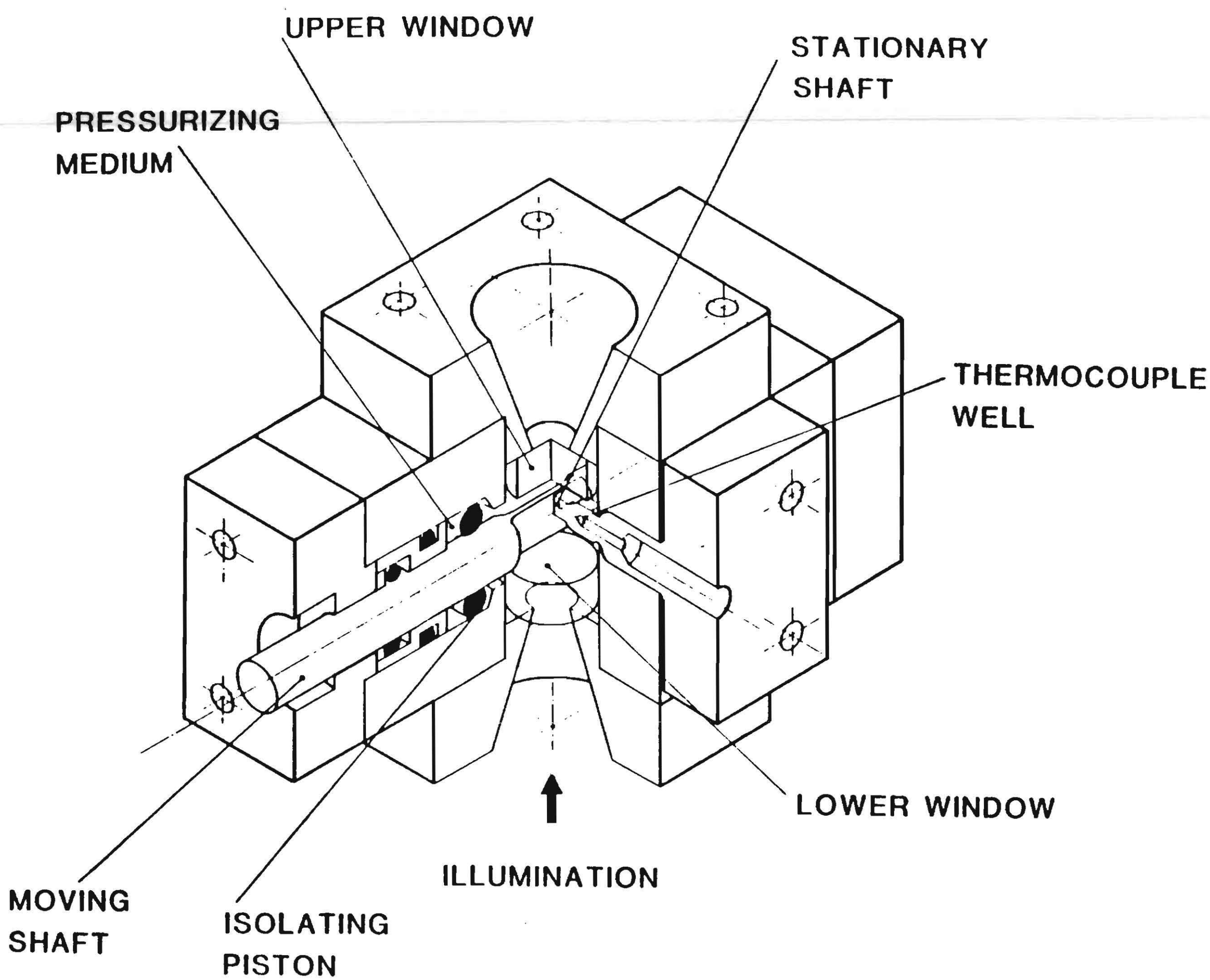


Fig. 3. High Pressure Flow Visualization Cell.

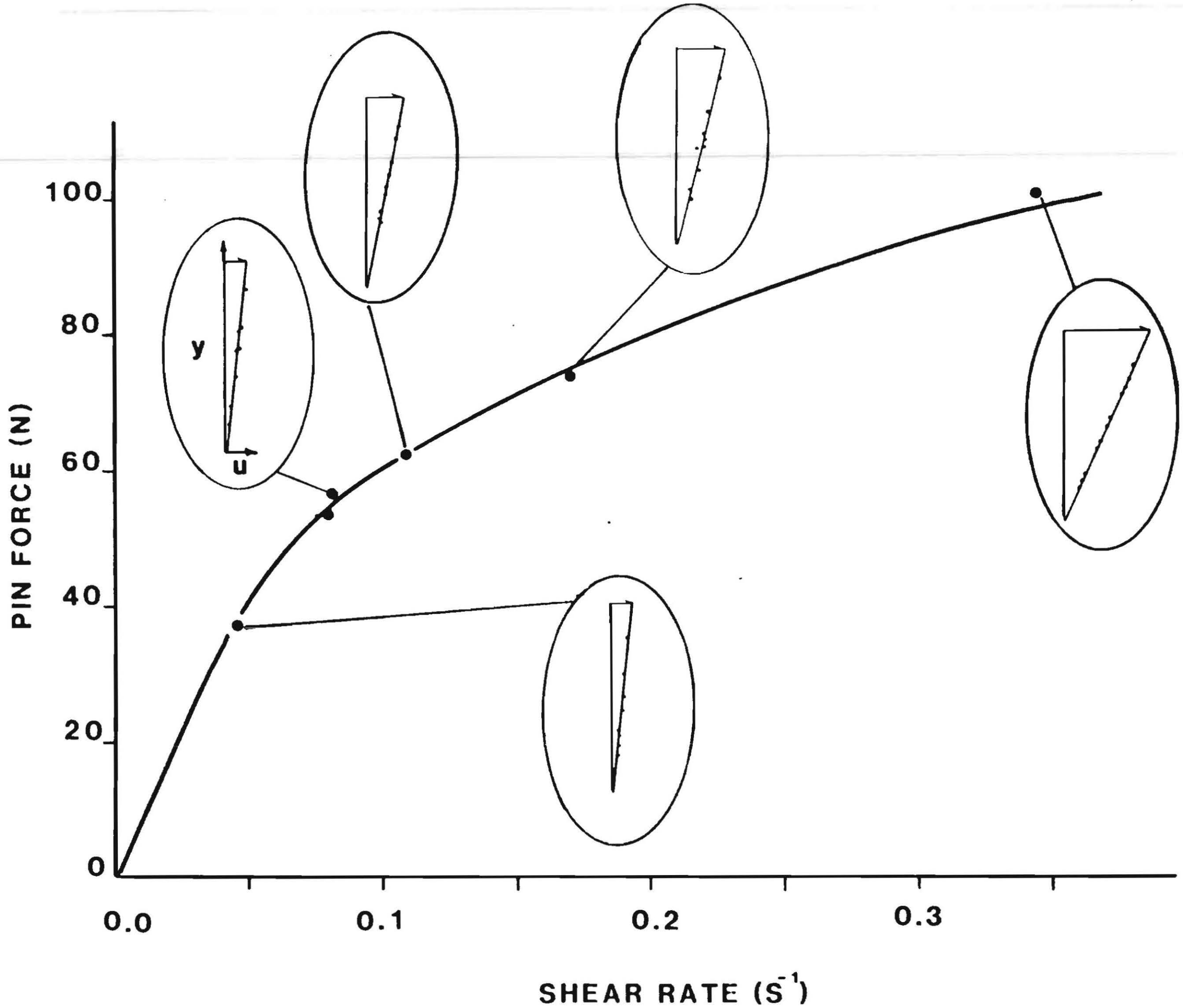


Fig. 4. Velocity Profiles in the Shear Gap with respect to Force Strain Rate Relationship.

5P4E at 151 MPa, 6 C

Fig. 5. Observed Shear Bands in the Shear Region.

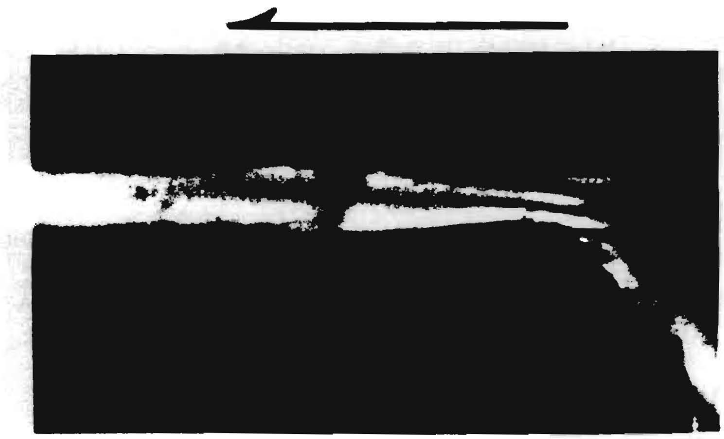


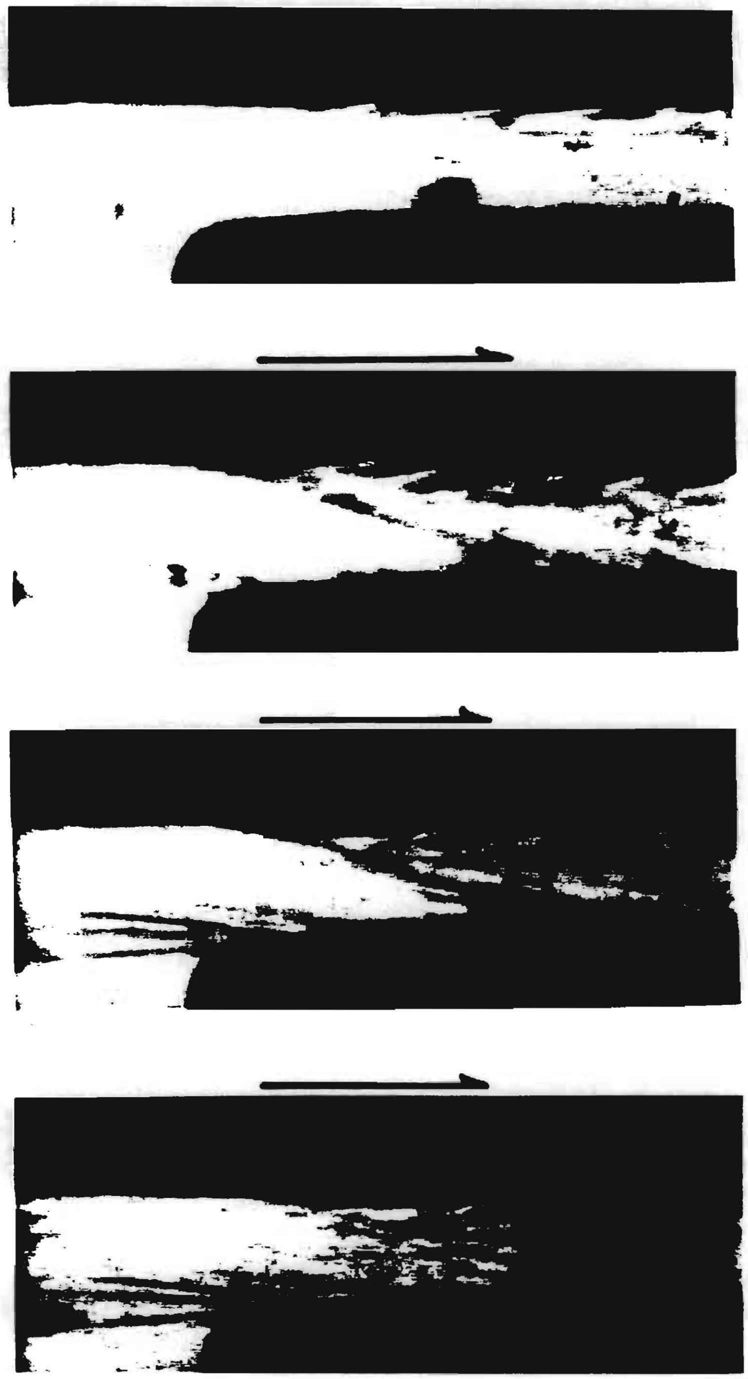
Fig. 6. Observed Birefringence in the Shear Region Under Crossed Polarized Light.

a

b

c

d



5P4E at 221 MPa, 23°C

Fig. 7. A Shear Band Operating in the Shear Region.

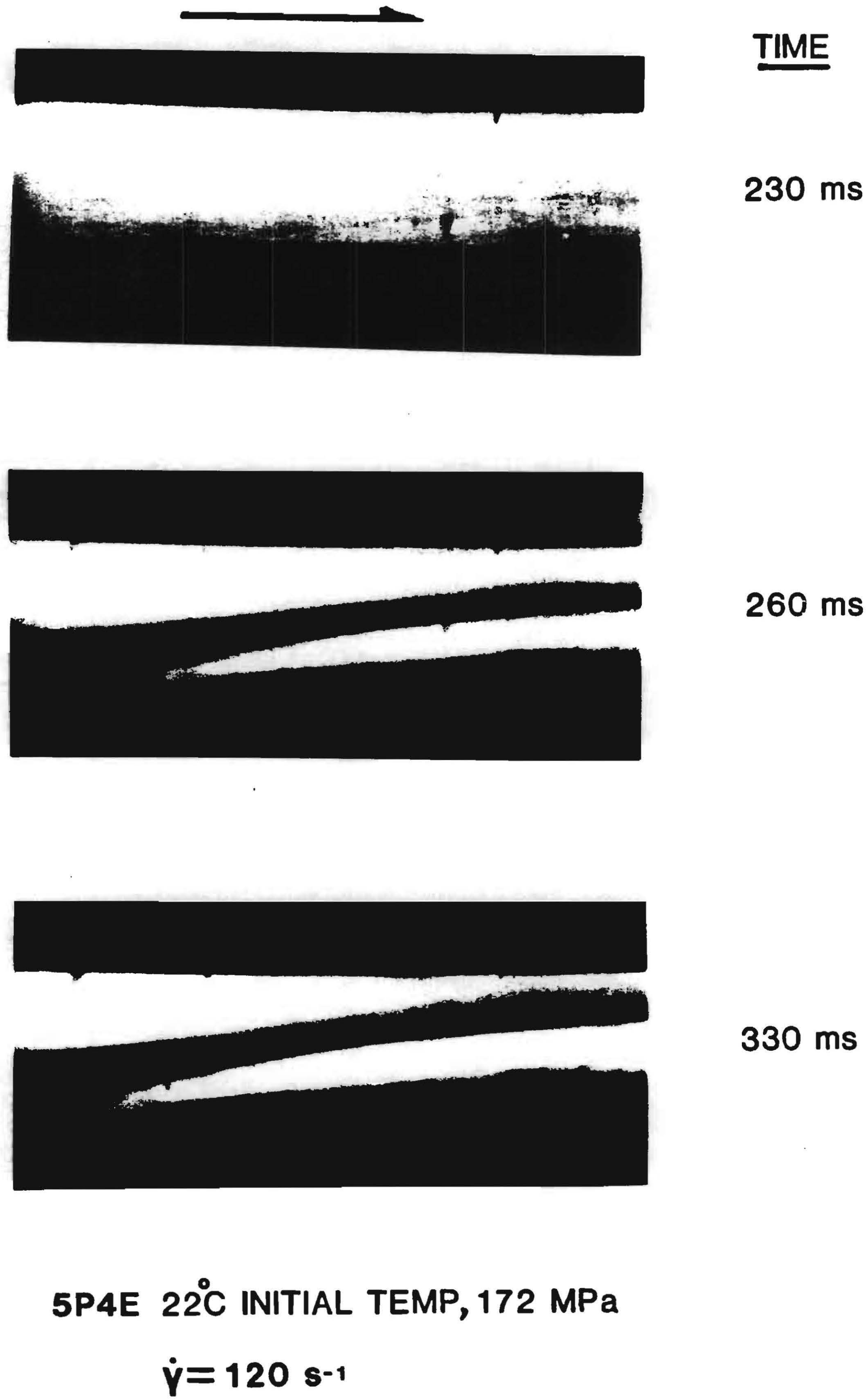


Fig. 8. Adiabatic Thermal Localization at High Shear Rate.

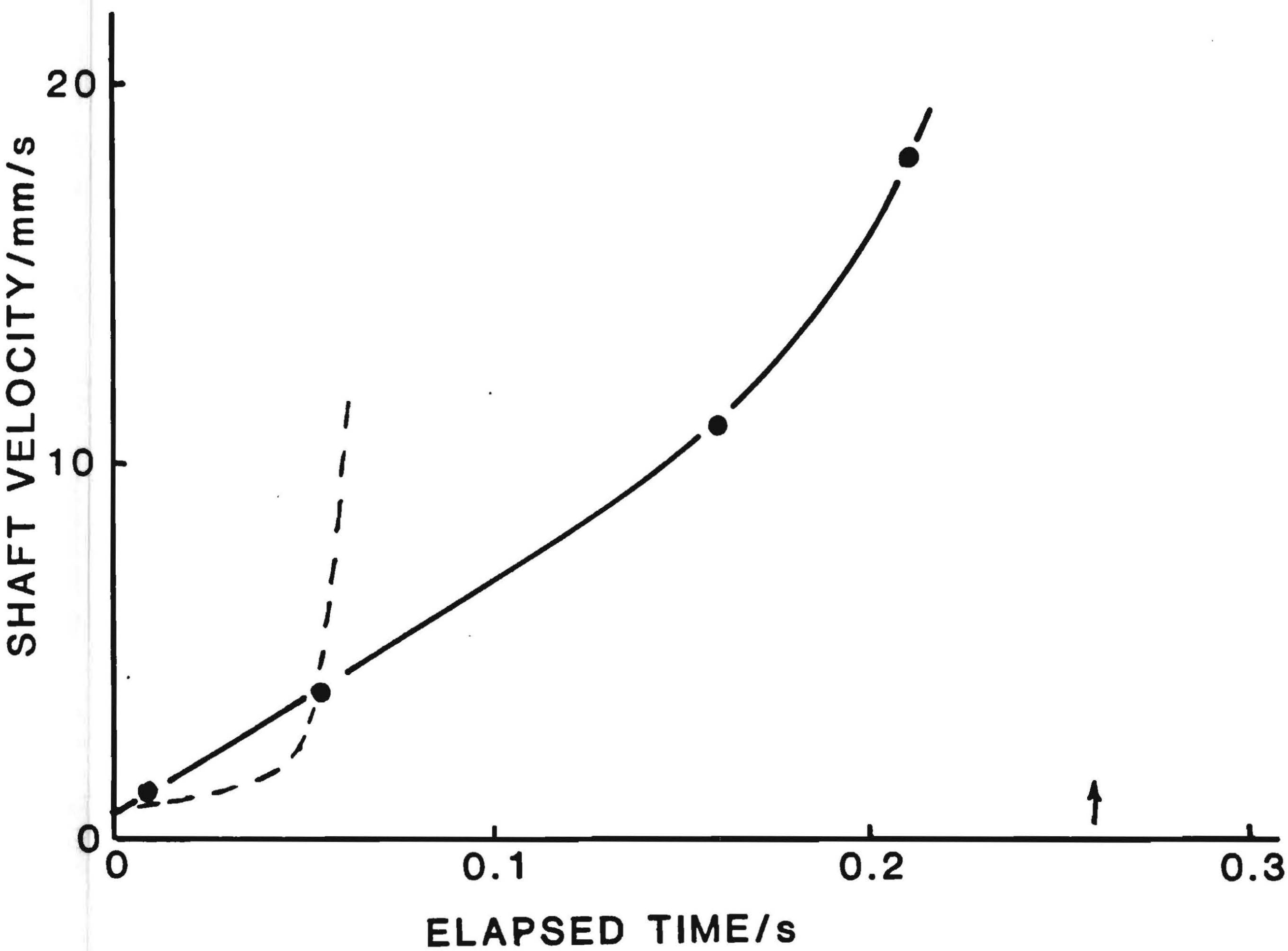


Fig. 9. Velocity History During Thermal Localization.